Graded Furrow Irrigation of Winter Wheat with Blocked Ends

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Abstract. *Winter wheat is widely irrigated by graded furrow application on the Central and Southern High Plains of the United States. A study was conducted to determine the effectiveness of blocking furrow ends and cutting-off furrow inflow earlier to eliminate runoff and save water, rather than using the common practice of 4- to 6-h runoff to wet the beds on the lower ends of fields. Earlier cutoff is feasible with wheat because flow retardance by the plants in furrows increases transient flow volume, thus causing soil wetting to closely follow furrow advance. Both adequate (3 to 4 applications) and deficit (1 to 2 applications) irrigation regimes were evaluated during the study. With adequate irrigation, the elimination of runoff with blocked furrows and earlier cutoff reduced average gross irrigation applications from 430 to 335 mm (16.9 to 13.2 in.) or 22% without reducing grain yield. Seasonal water use savings averaged 95 mm (3.8 in.) with adequate irrigation. With deficit irrigation, water savings were 17% or 48 mm (2 in.). Grain yields averaged 5.6 Mg/ha (83 bu/acre) and 4.2 Mg/ha (63 bu/acre), respectively, with adequate and deficit irrigation on blocked furrows.*
***Keywords.** Irrigation, Furrow irrigation, Wheat, Runoff.*

Winter wheat is widely irrigated with graded furrow application on the Central and Southern High Plains of the United States. Both adequate and varying levels of deficit irrigation management are practiced (Dusek and Musick, 1992). The climate is semiarid with annual precipitation ranging from 400 to 560 mm (16 to 22 in.). At Bushland, annual precipitation averages 475 mm (18.7 in.), and the 8.5 month (October through mid-June) winter wheat crop season averages 255 mm (10 in.). Evapotranspiration (ET) demands for adequately irrigated winter wheat in level basins ranged from 710 to 770 mm (28 to 30.3 in.) during a three-year study at Bushland by Dusek and Musick (1992). Their grain yields ranged from 5.0 to 8.2 Mg/ha (75 to 120 bu/acre) with adequate irrigation. About 35% of ET for adequately irrigated wheat at Bushland is supplied by precipitation whereas 40 to 50% of ET may be supplied by precipitation under deficit irrigation. Conventional practice, for graded furrow irrigation with bed-planted row crops, has been to allow about 6 h of runoff for more complete wetting of the lower end of fields. This practice has also been used for wheat being irrigated through 400 to 800 m (1/4 to 1/2 mile) furrows managed in 12- to 24-h sets. Previous research (Allen and Musick, 1972) indicated that this practice resulted in runoff volumes up to 20% of the water applied during four irrigations for winter wheat on 300 m (1000 ft) length plots with 1.0 m (40 in.) furrow spacing on a 0.3% grade. Runoff volume is increased by a relatively long duration of recession flow after irrigation cutoff. This relatively high transient flow volume is caused by the retardance effects of wheat plants in furrows having low grades, and by a low basic intake rate on fine-textured soils such as the Pullman clay loam at Bushland, Texas. Allen and Musick (unpublished) measured intake rates in furrows having small wheat plants (four weeks after emergence) on the Pullman soil during the fall of 1990 at Bushland. Intake rates after 8 h of application averaged 7.5 mm/h (0.3 in./h) using a flowing-furrow infiltrometer. Cumulative infiltration after 8 h averaged 140 mm (5.5 in.).

In a furrow-irrigated test with sorghum double cropped after winter wheat, recession flow times with clean-tilled 300-m (1000-ft) furrows averaged 1.6 h compared with 6.6 h for no-tilled furrows with standing wheat stubble (Allen and Musick, 1971). Tailwater reuse systems are widely used to reduce water application losses in furrow irrigation systems. However, design criteria used by the Soil Conservation Service in Texas estimate tailwater reuse system losses to be 20 to 35% of furrow runoff (Headings, 1993). Thus, graded furrow irrigation management to eliminate tailwater runoff and reuse system costs, is a desirable practice to save water, energy, and expense.

Chauhan et al. (1979) investigated blocked-end furrow systems and found it helpful to express furrow inflow cutoff in terms of advance distance as a function of furrow length rather than as a time function. Cutoff ratio (CR), as discussed herein, is defined as the furrow advance distance at cutoff/furrow length. Their CRs for maximum water distribution efficiency ranged from 0.6 to 0.9 for grades of 0.17 to 0.43%. Mandel et al. (1993) simulated blocked-end furrow irrigation for corn and conducted field trials on a silt loam in Nebraska. Their model usually underpredicted the distance that water ponded on the lower end of the field with blocked furrows.

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The very-limited, blocked-end furrow work reported in the literature involves bed-planted row crops without any plants growing in furrows. Blocked-end furrow research with wheat growing on both beds and furrows has not been reported. We hypothesized that vegetative retardance can be an advantage with steady-state furrow flow for wheat because of enhanced wetting of beds and increased water intake behind the advancing front in furrows with growing wheat plants. Therefore, the effect would allow furrow inflow cutoff when the advance front nears the end of the field rather than continuing application for 4 to 6 h of runoff after beds at the end of the field are already wetted.

Objectives of the field study were to:

- Determine the effectiveness of early furrow inflow cutoff in conjunction with blocked-end furrows that provide a limited amount of end-of-field surface storage and prevent tailwater runoff.
- Determine the effects of eliminating tailwater runoff using blocked-end furrows on reducing irrigation requirements, grain yield, and seasonal water use efficiency for a furrow irrigated wheat management system under both adequate and deficit irrigation levels.

Procedure

The field study was conducted during 1987 to 1990 on 1.0 m (40 in.) spaced graded furrows at the USDA Conservation and Production Research Laboratory, Bushland, Texas. The study evaluated open-end furrow treatments with tailwater runoff times of 4 to 6 h before irrigation cutoff, and an early cutoff blocked-end furrow treatment designed to allow some lower end ponding and the elimination of tailwater runoff. The deficit and adequate irrigation treatments were designed as two and four seasonal applications, respectively. The first irrigation was applied in the fall if surface soil wetting was needed to ensure crown root development during fall tillering. Spring irrigations were applied as needed with particular reference to the major growth stages—jointing in early April, booting stage in late April, anthesis in early May, and grain filling in late May. Development stages for irrigation application were based on previous research reported by Dusek and Musick (1992) and Schneider et al. (1969).

The experimental design was randomized block, split plot with three replications. Runoff control main plot treatments were split for irrigation level subplots. Main plots were 12.2 m (40 ft) wide × 400 m (1320 ft) long and contained 12 bed furrows on a 0.15% grade. Tests were conducted on a slowly permeable Pullman clay loam (fine mixed, thermic Torrertic Paleustoll) described by Unger and Pringle (1981). Plant available soil water storage capacity is about 240 mm (9.45 in.) to a 1.8 m (6 ft) rooting depth for water extraction by wheat.

Soil preparation consisted of disking and chiseling 15 cm (6 in.) deep after shredding the stubble, applying nitrogen as NH_3 at 135 kg (N)/ha [120 lb (N)/acre] and rebedding. The TAM 200 wheat variety was planted 29 September 1987; 1 October 1988; and 25 September 1989 by grain drill in 20 cm (8 in.) spaced rows. Three wheat rows were located on the bed and two in the furrow.

Irrigation was applied through gated pipe and measured with a propeller meter. Individual furrow inflow rates were measured volumetrically and adjusted to the selected application rate planned to achieve targeted application times of 16 to 24 h. Individually calibrated "H" flumes, equipped with water level recorders, were used to measure furrow runoff from the four center furrows of each open-end furrow plot. A commercially available PC computer interface "digitizing tablet" was used to read flow depths from flume runoff hydrographs. Soil water contents were measured gravimetrically by 0.3 m (1 ft) increments to the 1.8 m (6 ft) depth before and after irrigations at 30, 200, 300, and 365 m (100, 650, 1000, and 1200 ft) sites along the 400 m (1320 ft) length of furrow. Additional soil water content sites near the end of blocked furrows were located at 350, 360, and 370 m (1140, 1180, and 1220 ft), respectively, to determine the effect of temporary lower-field surface storage. Seasonal water use (ET) was determined by the water balance method using beginning and end of season soil profile water contents, net irrigation, and precipitation. Water use efficiency (WUE) was determined as the ratio of grain yield to seasonal ET (including net irrigation). Irrigation water use efficiency (IWUE) was determined as the ratio of irrigated grain yield minus dryland yield to net irrigation. Grain yield was determined by plot combining 1.5- × 12-m (5- × 40-ft) strips centered on the sites listed for sampling soil water content. Grain yields are reported as 12.5% moisture, wet basis. Treatment means in individual years were analyzed for variance through use of Statgraphics (1992).

Results and Discussion

During the second year of the study, the 1988-1989 crop was destroyed by hail and these data are not reported. Data reported herein are for the 1987-1988 and the 1989-1990 crop years. Treatment effects on irrigation application and recession flow duration, gross irrigation application, and runoff are presented for each irrigation in tables 1 and 2. Seasonal irrigation, ET, grain yield, and WUE are presented in table 3. Soil water content and grain yield with length of furrow run are presented in figures 2, 3, and 4.

Seasonal Precipitation and Irrigation Requirement

Long-term cumulative precipitation for the October through mid-June wheat season is presented in figure 1 for comparison with that received during the 1987-1988 and 1989-1990 crop seasons. In the first crop season, precipitation was 303 mm (11.9 in.) or 19% above average. In contrast, precipitation during the 1989-1990 crop season was only 127 mm (5 in.) or 50% of average.

1987-1988 Season. In September, 1987, surface soil water content was adequate for seeding and emergence but the lower profile was relatively dry. Plant available soil water content (ASW) to the 1.8 m (6 ft) depth in mid-October (fig. 2) was less than 20% of field capacity (FC). Timely late fall precipitation [85 mm (3.3 in.)] occurred, assuring adequate soil water content to the 0.5 m (1.5 ft) depth for crown root development without a late fall irrigation. April through May precipitation totaled 152 mm (6 in.) which was 70% above average. This relatively high spring rainfall greatly benefitted the limited irrigation

Table 1. Furrow flow rate, set and recession flow time, application and runoff, 1988, Bushland, Tex.

Treatment	Flow Rate (L/s*)	Applic Time (h)	Recess Flow (h)	Gross Applic (mm)	Runoff (mm)	Runoff (%)
Runoff Furrows						
Adeq. Irrig.						
3/25/88	0.88	21.0	6.7	165	15.2	9.0
4/28/88	0.63	22.5	6.0	127	7.1	5.6
5/12/88	0.63	15.2	4.0	86	2.5	3.0
Average		19.6	5.6	126	8.3	5.9
Total				378	24.8	
Deficit Irrig.						
4/28/88	0.88	24.0	4.0	189	10.2	5.5
5/25/88	0.63	27.0	6.0	152	15.2	10.0
Average		25.5	5.0	170	12.7	7.8
Total				341	25.4	
Blocked-end Furrows						
Adeq. Irrig.						
3/25/88	0.88	16.4		130		
4/28/88	0.63	18.6		105		
5/12/88	0.63	12.1		68		
Average		15.7		101		
Total				303		
Deficit Irrig.						
4/28/88	0.88	19.6		156		
5/25/88	0.63	24.0		133		
Average		21.8		144		
Total				289		

* Metric to English unit conversion: 1 L/s = 16 gpm, 25 mm = 1 in.

Table 2. Furrow flow rate, set and recession flow time, application and runoff, 1989-1990, Bushland, Tex.

Treatment	Flow Rate (L/s*)	Applic Time (h)	Recess Flow (h)	Gross Applic (mm)	Runoff (mm)	Runoff (%)
Runoff Furrows						
Adeq. Irrig.						
11/13/89	0.63	20.5	8.0	116	14.5	12.5
4/12/90	0.63	18.0	6.0	102	9.4	9.0
5/9/90	1.00	14.6	7.5	130	24.4	19.0
5/24/90	1.00	15.0	5.0	134	18.5	14.0
Average		17.0	6.6	120	16.7	
Total				482	66.8	
Limit. Irrig.						
11/13/89	0.63	20.5	8.0	116	14.5	12.5
4/12/90	0.63	18.0	6.0	102	9.4	9.0
Average		19.2	7.0	109	12.0	
Total				218	23.9	
Blocked-end Furrows						
Adeq. Irrig.						
11/13/89	0.63	16.3		92		
4/12/90	0.63	14.4		81		
5/9/90	0.76	14.6		99		
5/24/90	0.76	14.0		95		
Average		14.8		92		
Total				367		
Limit. Irrig.						
11/13/89	0.63	16.3		92		
4/12/90	0.63	14.4		81		
Average		15.4		87		
Total				173		

* Metric to English unit conversion: 1 L/s = 16 gpm, 25 mm = 1 in.

treatments. Late May rainfall eliminated the need to apply a planned late season irrigation on the W-2 treatments, thus the net irrigation to W-1 treatments was almost as much as for the W-2 treatments (table 3).

1989-1990 Season. In late September 1989, surface soil water contents were adequate for crop emergence. However, an irrigation was needed by 13 November 1989 to allow crown roots to develop because of dry surface soil. During the spring and early summer growing season of 1990, April-June precipitation was only 25% of average or 38 mm (1.5 in.) which increased irrigation demand (table 2). In addition to the spring drought, relatively high May-June temperatures increased ET demand. After the final irrigation for the adequate treatment on 24 May 1990, the ASW was about 220 mm (8.7 in.). This ASW, plus anticipated rainfall, would usually be adequate to supply ET demands because the May-15 June period has a high (85%) probability for receiving 60 mm (2.36 in.) of rainfall in the Bushland area. This expected rainfall is usually helpful for maturing wheat or establishing sorghum (Allen and Musick, 1990). However, in 1990 the ET demand for wheat at Bushland, as measured with weighing lysimeters (Steiner et al., 1991), was 250 mm (9.8 in.) between 24 May (last irrigation on adequate treatment) and physiological maturity on 22 June. Thus, the adequate treatments were under light stress during final days of grain filling.

Irrigation Set and Recession Flow Duration – Runoff

In the 1987-1988 season, the use of blocked furrows reduced average application time and total gross application by about 20% with adequate irrigation and by 15% with deficit irrigation (table 1). Recession flow with open-end furrows averaged 5.6 h with adequate irrigation and 5 h with limited irrigation (table 1). Runoff averaged 6% of gross application with adequate irrigation and 8% with deficit irrigation. In the experimental design, inflow cutoff to blocked furrows was planned when the advance front neared the ends of furrows (90 to 95% of furrow length). This proved to be a valid decision for early season applications before vegetation significantly retarded the advance rate and increased the furrow flow volume by increasing depth of flow. For later applications, it was determined necessary to cut off inflow when the advance front had reached about 75% of the furrow length [300 m (1000 ft)] in order to prevent excessive ponding or break-over from recession flow accumulation on the lower end of

Table 3. Treatment effects on water applied, profile depletion, ET, and WUE, Bushland, Tex.

Treatment	Precip (mm†)	Irrig. Net (mm)	Profile Deplete (mm)	ET (mm)	Grain Yield (Mg/ha)	WUE (kg/m³)	IWUE* (kg/m³)
1987-1988							
Def Irrig.	303	315	−13	605ab‡	5.11b	0.84b	1.16b
Def Irrig., Bl		289	−38	554b	5.04b	0.91ab	1.24b
Adq Irrig.		353	0	656a	5.85a	0.89ab	1.24b
Adq Irrig., Bl		303	−3	603a	5.97a	0.99a	1.50a
1989-1990							
Def Irrig.	127	191	198	516b	3.15b	0.61c	1.02bc
Def Irrig., Bl		173	185	485b	3.36b	0.69b	1.24a
Adq Irrig.		415	191	733a	4.97a	0.68b	0.91c
Adq Irrig., Bl		367	173	667a	5.22a	0.78a	1.09bc
Mean							
Def Irrig.	215	253	92	560	4.13	0.74	1.09
Def Irrig., Bl		231	74	520	4.20	0.81	1.24
Adq Irrig.		384	95	694	5.41	0.78	1.08
Adq Irrig., Bl		335	85	635	5.60	0.88	1.30

* Subtracted dryland grain yields of 1.44 Mg/ha in 1988 and 1.21 Mg/ha in 1990.

† Metric to English unit conversion:
25 mm = 1 in.
1 Mg/ha = 14.9 bu/acre
1 kg/m³ = 3.8 bu/acre-in.

‡ Variables followed by the same letter in individual years are not significantly different at the 5% level according to Duncan's Multiple Range Test.

blocked furrows. This result is similar to that experienced by Mandel et al. (1993) where the distance ponded by blocked furrows on the lower end exceeded expectations. Our optimum CR of 0.75 is within the range of 0.6 to 0.9 reported by Chauhan et al. (1979).

In the 1989-1990 season (table 2), total gross application with open furrow adequate irrigation was 482 mm (19 in.) compared with 367 mm (14.4 in.) for blocked-end furrows, a 24% reduction. For the deficit irrigation treatment, blocked-end furrows reduced gross application by 21%.

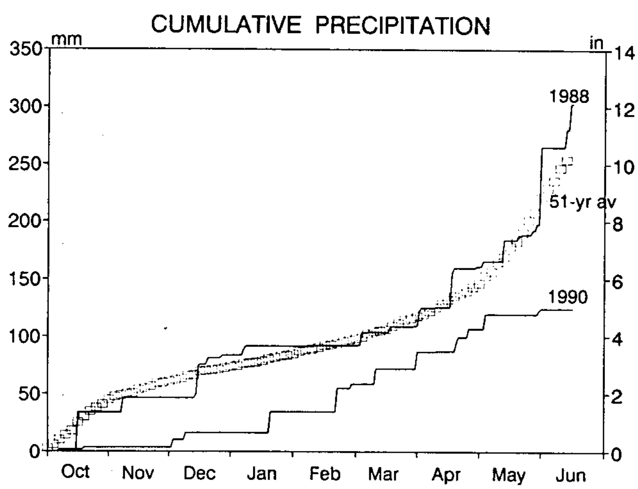

Figure 1–Cumulative October through mid-June seasonal rainfall during the two study years compared with 51-year cumulative average at Bushland, Tex.

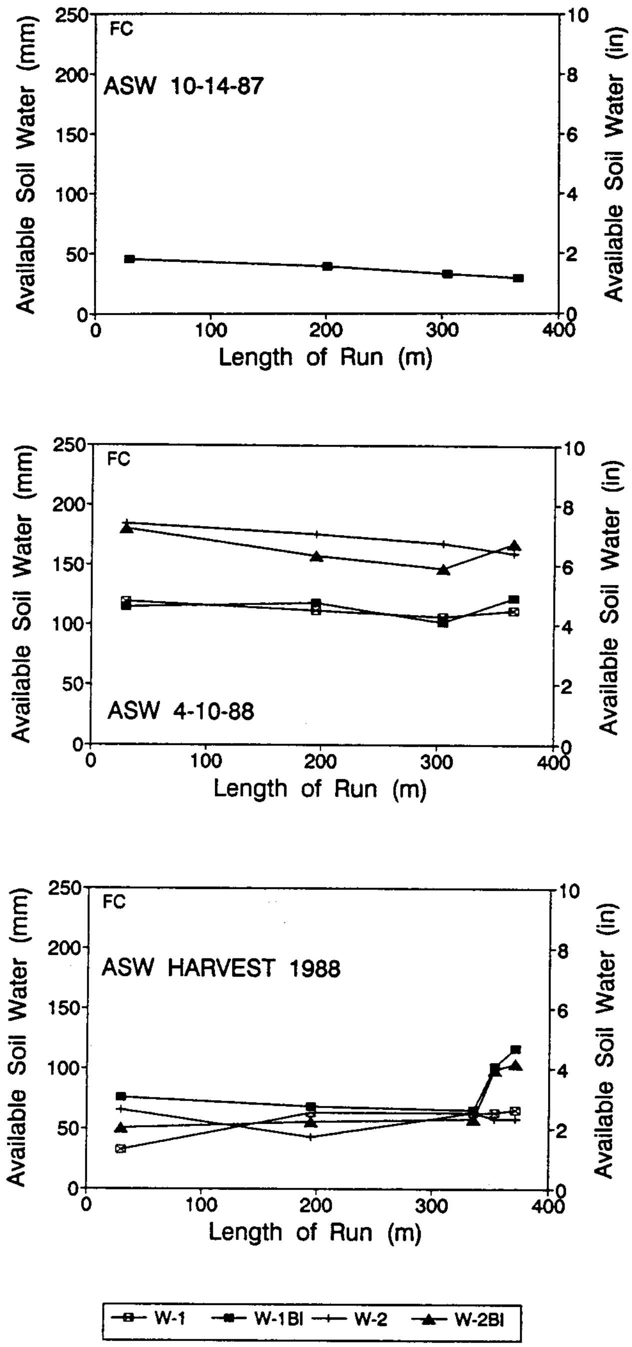

Figure 2–Plant available soil water content to 1.8 m (6 ft) depth along length of furrow run after fall planting, two weeks after first spring irrigation, and at harvest, 1988 (1 m = 3.28 ft).

Runoff from open furrow treatments, expressed as a percentage of the applied irrigation volume, averaged 6.9% in 1988 and 12.2% in 1990. The two-year average of 9.5% was substantially less than up to 20% reported by Allen and Musick (1972). Recession flow averaged 6 h or about 30% of irrigation set times and is comparable to earlier research results with wheat (Allen and Musick, 1971).

Soil Water Distribution and Storage

For the 1987-1988 season, the differences in ASW content between the deficit and adequate irrigation treatments two weeks after the first irrigation are illustrated

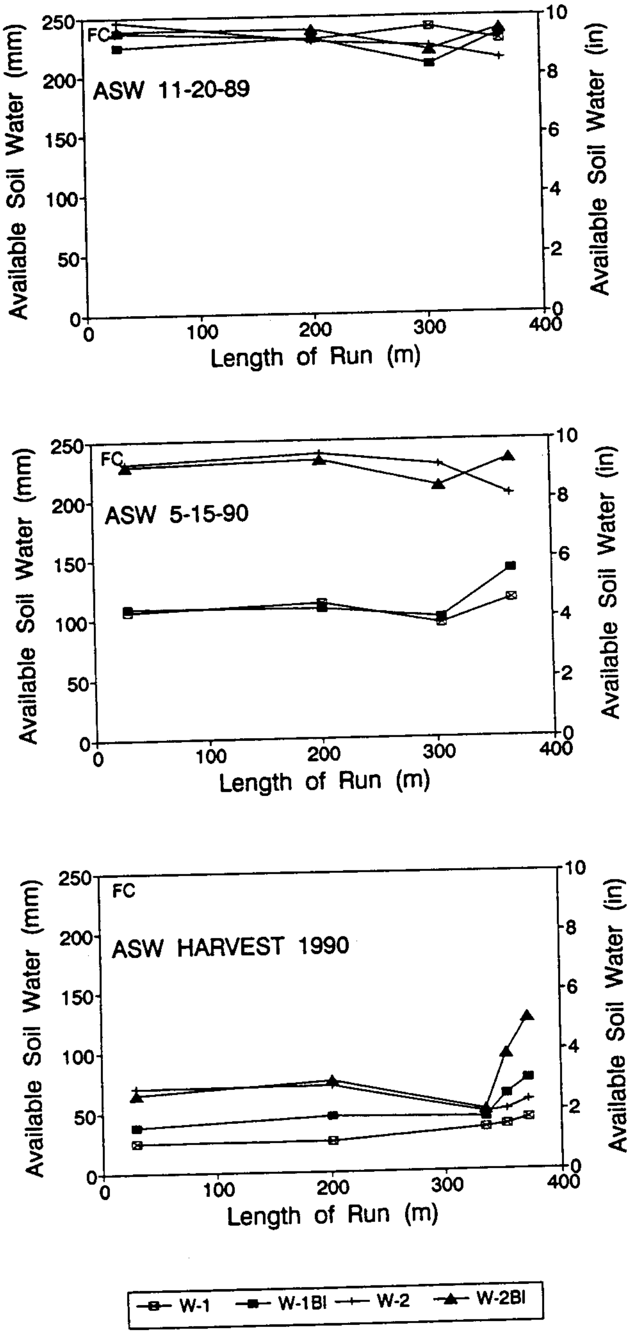

Figure 3–Plant available soil water content to 1.8 m (6 ft) depth along length of furrow run after fall irrigation, after early May irrigation, and at harvest, 1990 (1 m = 3.28 ft).

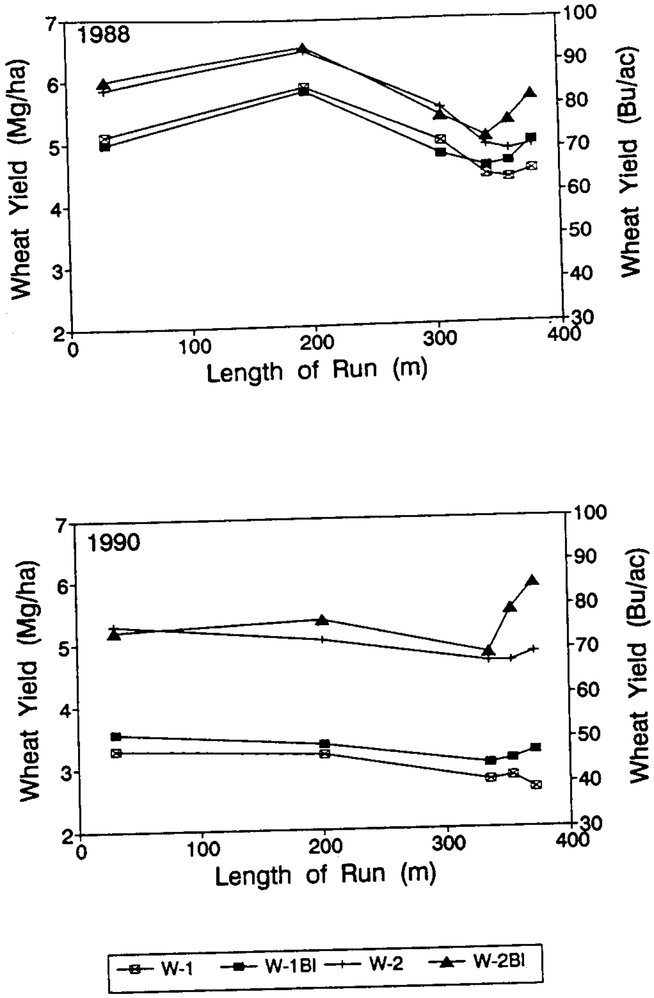

Figure 4–Wheat yield along length of furrow run in 1988 and 1990 (1 m = 3.28 ft).

in figure 2. The deficit treatments, which had not yet received an irrigation on 10 April were at about 50% of FC and the adequate treatments were at about 75% of FC. Soil water contents at harvest (1 July) had declined to about 25% of FC (fig. 2). The effects of blocked-end furrows increasing soil water storage near the lower end of the furrows is evident where the last 50 m (160 ft) had about double the ASW of open furrows.

In the 1989-1990 season, the fall irrigation nearly filled the profile for all treatments (fig. 3). By 15 May 1990, the ASW for the deficit treatment had declined to near 50% of FC (fig. 3). By harvest time (fig. 3), the W-2 treatments had ASW depletion to about 30% of FC. The W-1 treatments depleted ASW contents to only 15 to 20% of FC and the wheat experienced major water stress. The furrow blocking effect on lower-end soil water storage is shown by about 125 mm (5 in.) ASW at the lower end for the W-2 treatment. Even the deficit irrigation treatment had about 35 mm (1.4 in.) more stored water at the blocked furrow end, compared with open furrows. The reduced soil water storage at the 300 to 340 m furrow distance, as compared with the upper 1/2 of the furrow length in the spring and at harvest, illustrates that irrigation intake and profile storage can be reduced on the lower 1/4 of the furrow length because of reduced opportunity time. This moderate deficit soil water storage on the lower 1/4 is the result of managing the overall irrigation application to avoid deep percolation losses on the upper 1/2 and to avoid excessive ponding and percolation on the lower end with blocked furrows.

Irrigation Water Use, ET, Grain Yield, and WUE

Gross seasonal irrigation application with adequate irrigation was reduced by an average of 22% through the use of blocked furrows and earlier cutoff or reduced flow rate to eliminate runoff, with only minor affect on grain yield (tables 2 and 3). This water saving amounted to

75 mm (3 in.) in 1988 and 115 mm (4.5 in.) in 1990, and averaged 95 mm (3.8 in.).

Plant stands were reduced near the upper end of the field in 1988, which is reflected in the highest grain yields occurring at the mid-point of the furrow length (fig. 4). The additional ASW storage near the end of blocked furrows increased grain yield, but acreage effect on yields for the entire furrow length were minor. Grain yields for deficit treatments in 1988 were about 90% of those for adequate treatments because of the beneficial effects of above average spring rainfall (table 2). Accordingly, seasonal ET values for deficit treatments were also about 90% of those for adequate treatments. In 1990, grain yields (table 2 and fig. 4) were lower because of higher ET associated with high evaporative demand during May through physiological maturity in mid-June.

Average grain yields for blocked furrows were similar to those with open furrows under both irrigation levels. Consequently, blocked furrows achieved a higher seasonal WUE and IWUE because of less water application and the elimination of runoff losses (table 3). The average blocked-furrow WUEs of 0.81 and 0.88 kg/m^3 (3.0 and 3.3 bu/acre-in.) for deficit and adequate irrigation respectively, are within the range of 0.78 to 0.93 kg/m^3 (2.9 to 3.5 bu/acre-in.) reported by Dusek and Musick (1992) with winter wheat grown in level basins during 1988 and 1990 at Bushland. At the same time, blocked-furrow IWUEs averaged 1.3 kg/m^3 (4.9 bu/acre-in.) which were nearly equal to the 1.25 kg/m^3 (4.7 bu/acre-in.) achieved by Dusek and Musick (1992) in level basins.

The blocked furrow treatment increased average IWUE from 1.09 to 1.24 kg/m^3 (4.1 to 4.7 bu/acre-in.) or 14% with deficit irrigation, and from 1.09 to 1.3 kg/m^3 (4.1 to 4.9 bu/acre-in.) or 20% with adequate irrigation. Under the same conditions, average WUEs were 9 and 13% higher, respectively, with deficit and adequate irrigation. These results reveal that winter wheat production can be increased efficiently by supplementing precipitation with limited irrigation amounts for moderate yields of 3.3 to 4 Mg/ha (50 to 60 bu/acre) or for full production yields of 5.4 to 6 Mg/ha (80 to 90 bu/acre) with adequate irrigation. Annually cropped dryland wheat averages 1 to 1.3 Mg/ha (15 to 20 bu/acre) at Bushland.

Conclusions

The study confirms the possibility of eliminating runoff for graded furrow irrigation of wheat on fine textured soils with moderate slopes by blocking furrow ends. The conclusions from the study follow.

- Earlier irrigation cutoff is possible with wheat because vegetative retardance in furrows slows advance, increases transient flow volume, and results in beds being wetted closely behind the advancing front.
- Gross irrigation applications may be reduced up to about 20% because of earlier cutoff with blocked-end furrows without reducing grain yield.
- The reduced irrigation application with blocked-end furrows results in water use efficiencies similar to those achievable with level basin irrigation.
- The reduced water application and runoff elimination with blocked furrows can permit irrigating larger areas from a fixed water supply.

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